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Trajectory Selection for the Mariner Jupiter/Saturn 1977 Project

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PREFACE

The work described in this report was performed by the Mariner Jupiter/Saturn 1977 Project of the Jet Propulsion Laboratory.

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ABSTRACT

This article describes the use of decision analysis to facilitate a group decision-making problem in the selection of trajectories for the two spacecraft of the Mariner Jupiter/Saturn 1977 Project. This NASA project includes the participation of some 80 scientists divided by specialization among 11 science teams. A set of 32 candidate trajectory pairs was developed by the Project in collaboration with the science teams. Each science team then ordinally ranked and assigned cardinal utility function values to the trajectory pairs. The data and statistics derived from collective choice rules were used by the scientists in selecting the science-preferred trajectory pair.

INTRODUCTION

This article describes the use of decision analysis to facilitate a group decision-making problem in the selection of trajectories for the Mariner Jupiter/Saturn 1977 (MJS77) Project. The objectives of the MJS77 Project are to conduct science investigations of the Jupiter and Saturn planetary systems and the interplanetary space between Earth and Saturn (Refs. 1 and 2). This project is funded in excess of $300 million and is managed for NASA by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. NASA has selected some 80 scientists, divided by specialization among 11 science teams, to participate on the MJS77 mission. The science investigations to be performed are shown in Table I. The scientists interface with the Project through a Science Steering Group (SSG) composed of the team leaders of the science teams. At the time this decision analysis was performed, 10 of the 11 science teams had been selected.

Two MJS77 spacecraft will be launched by NASA in August and September 1977 on a pair of trajectories that will swing by Jupiter in 1979, encounter Saturn in late 1980 or early 1981, and then escape the solar system (Fig. 1). The spacecraft design is based on the Mariner experience, augmented in capability to meet the requirements for long-life, long-range communications, precision navigation, solar independent power, and support of the science investigations (Fig. 2). The spacecraft will be launched by a Titan III-E/ Centaur D-1T plus a solid-rocket kick stage to obtain the necessary launch energy.

The selection of the trajectories for the mission is a major Project decision, since the trajectory characteristics will significantly affect the science investigations. At a meeting on October 22 and 23, 1973, a pair of trajectories was selected and recommended by the SSG for incorporation as the Project standard trajectory pair. While this trajectory pair may not actually be flown, nevertheless it represents a commitment on the part of the scientists, because the Project systems will be designed to this standard trajectory pair. Thus the selection of the standard trajectory pair was viewed as an important milestone, both by the Project and by the scientists.

A decision analysis was performed prior to the October meeting of the SSG to facilitate the trajectory pair selection process. Because of the requirement that the trajectory pair recommended by the SSG should be based

Table I

The MJS77 Science Investigations

SCIENCE TEAM	ABBREVIATION	PRIMARY MEASUREMENTS
RADIO SCIENCE	RSS	PHYSICAL PROPERTIES OF ATMOSPHERES AND IONOSPHERES. PLANET AND SATELLITE MASSES, DENSITIES, AND GRAVITY FIELDS. STRUCTURE OF SATURN RINGS
INFRARED RADIATION	IRIS	ENERGY BALANCE OF PLANETS. ATMOSPHERIC COMPOSITION AND TEMPERATURE FIELDS. COMPOSITION AND PHYSICAL CHARACTERISTICS OF SATELLITE SURFACES AND SATURN RINGS
IMAGING SCIENCE	ISS	IMAGING OF PLANETS AND SATELLITES AT RESOLUTIONS AND PHASE ANGLES NOT POSSIBLE FROM EARTH. ATMOSPHERIC DYNAMICS AND SURFACE STRUCTURE
PHOTOPOLARIMETRY	PPS	METHANE, AMMONIA, MOLECULAR HYDROGEN, AND AEROSOLS IN ATMOSPHERES. COMPOSITION AND PHYSICAL CHARACTERISTICS OF SATELLITE SURFACES AND SATURN RINGS
ULTRAVIOLET SPECTROSCOPY	UVS	ATMOSPHERIC COMPOSITION INCLUDING THE HYDROGEN TO HELIUM RATIO. THERMAL STRUCTURE OF UPPER ATMOSPHERES. HYDROGEN AND HELIUM IN INTERPLANETARY AND INTERSTELLAR SPACE
COSMIC RAY PARTICLES	CRS	ENERGY SPECTRA AND ISOTOPIC COMPOSITION OF COSMIC RAY PARTICLES AND TRAPPED PLANETARY ENERGETIC PARTICLES
LOW ENERGY CHARGED PARTICLES	LECP	ENERGY SPECTRA AND ISOTOPIC COMPOSITION OF LOW ENERGY CHARGED PARTICLES IN PLANETARY MAGNETOSPHERES AND INTERPLANETARY SPACE
MAGNETIC FIELDS	MAG	PLANETARY AND INTERPLANETARY MAGNETIC FIELDS
PLASMA PARTICLES	PLS	ENERGY SPECTRA OF SOLAR-WIND ELECTRONS AND IONS, LOW ENERGY CHARGED PARTICLES IN PLANETARY ENVIRONMENTS, AND IONIZED INTERSTELLAR HYDROGEN
PLANETARY RADIO ASTRONOMY	PRA	PLANETARY RADIO EMISSIONS AND PLASMA RESONANCES IN PLANETARY MAGNETOSPHERES
PLASMA WAVES*	PWS	ELECTRON DENSITIES AND LOCAL PLASMA WAVE-CHARGED PARTICLE INTERACTIONS IN PLANETARY MAGNETOSPHERES

*NOT SELECTED BY NASA AT THE TIME OF THIS STUDY

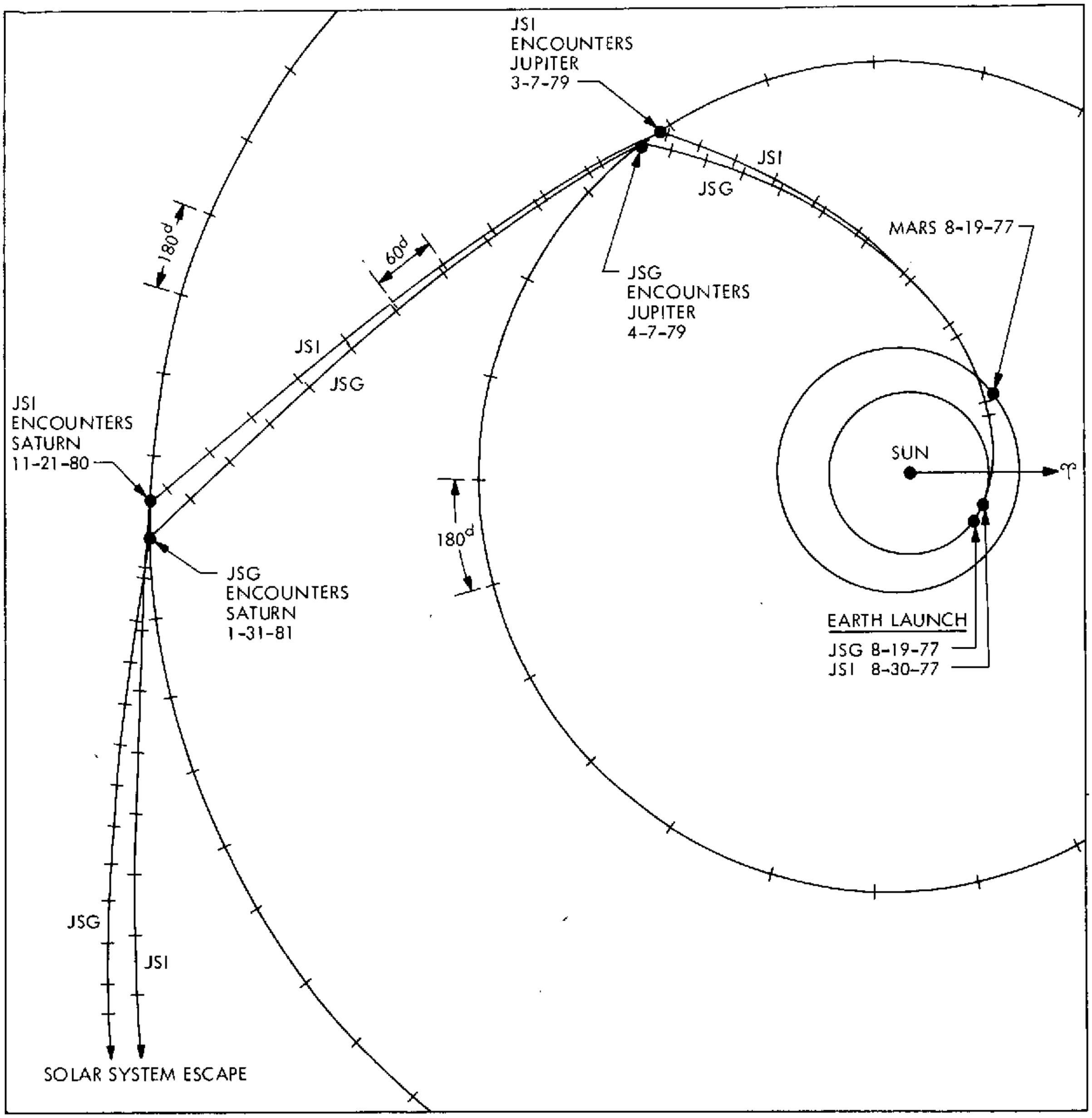

Figure 1. Heliocentric View Showing the Selected Trajectory Pair (JSI and JSG).

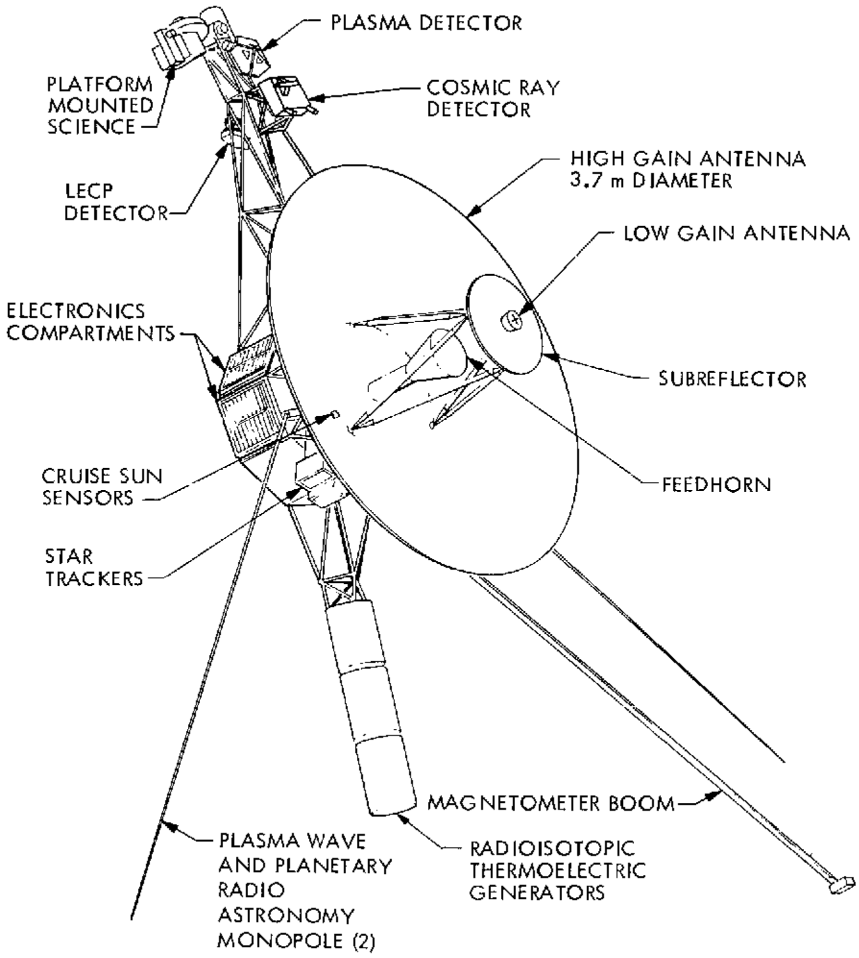

Figure 2. The MJS77 Spacecraft.

on a consensus, this analysis was guided by the principles of certain collective choice rules, rather than by principles assuming a single decision-maker. This analysis provides the only example of the use of these formal concepts of collective choice in actual decision-making for a significant, real-world situation of which the authors are aware.

The plan of this article is as follows. Following this introduction, Section II reviews the analyses performed for trajectory selection for previous Mariner projects. Section III describes the MJS77 trajectory characteristics. Section IV presents an overview of the MJS77 trajectory selection process. Section V describes the development of the candidate trajectory pairs by the Project and the science teams. Section VI describes the evaluation of the candidate trajectory pairs by the individual science teams. Section VII describes the collective choice analysis performed by the Project. Section VIII presents the deliberations of the scientists at the SSG meeting. Section IX presents a post-selection evaluation by the scientists of the trajectory pair selection process. The conclusions are summarized in Section X.

II. PREVIOUS SELECTION PROCESSES FOR MARINER TRAJECTORIES

All previous Mariner Projects have considered science requirements in the selection of trajectories for the missions. The earliest Mariner flights (Mariner 2 encountered Venus in 1962 and Mariner 4 encountered Mars in 1965), with their relatively large targeting errors and with simple science sequences at the encountered planet, did not require extensive analysis of alternative trajectories vis-a-vis science.

The first extensive analyses of trajectory requirements for science were performed on the Mariner Venus 1967 Project for Mariner 5 (Ref. 3) and on the Mariner Mars 1969 Project for Mariners 6 and 7 (Ref. 4). In the Mariner Mars 1969 analysis, science "value functions" for the six science investigations were constructed over the feasible trajectory space for three science platform slewing strategies. These value functions operationally had an ordinal strength of measurement. Total value functions were then constructed by adding the individual value functions according to three weighting schemes. The results of this parametric analysis were presented to the scientists, and the flight trajectories were then selected in a meeting between the scientists and the Project Manager.

For the Mariner Mars 1971 Project, which placed Mariner 9 in orbit around Mars on November 14, 1971, no formal trajectory selection analysis with respect to science value was documented. The mission originally consisted of two Mars orbiters. One of the orbiters was to be placed in a high-inclination ($i \approx 80$ deg) orbit at Mars to obtain total surface coverage. The other was to be placed in a moderate-inclination ($i \approx 50$ deg) orbit to obtain repeated coverage for identification of time-varying surface features. When the first of the two launches failed, the second spacecraft was then targeted for a compromise orbit at Mars with an inclination angle of 65 deg (Ref. 5).

The formal trajectory analysis of the type developed on the Mariner Mars 1969 Project was extended for the Mariner Venus/Mercury Project, which launched Mariner 10 on a flight to Venus and Mercury on November 3, 1973. Ordinal science value functions were constructed over the feasible trajectory space for each of the seven science investigations (Ref. 6). Two total science value functions were then formed, one by an additive and the other by a multiplicative combination of the individual science value functions. Unity weighting schemes were used in both cases. The multiplicative science value function was examined to test the sensitivity of the results to large losses in science value by one or two investigations. As a result of this analysis, the launch of Mariner 10 was delayed from October 14 to November 3, 1973. The Mercury arrival date of March 29, 1974, was also selected on the basis of the analysis.

III. THE MJS77 TRAJECTORY CHARACTERISTICS

The feasible trajectories that can be considered for Earth/Jupiter/Saturn missions are constrained by a number of astrodynamic and programmatic factors. Flights direct from Earth to Saturn with flight times less than six years are presently not possible with existing launch vehicles within the total dollar constraints of the Project. Opportunities to fly missions to Saturn via a swingby of Jupiter occur approximately every 20 years, with a significantly reduced flight time. The next opportunity occurs in the 1976-1980 time period, with the most favorable launch dates in August and September 1977 (Ref. 7).

The requirement to proceed on to Saturn almost totally constrains the arrival point at Jupiter. For a given arrival date at Saturn and a given launch date at Earth, the arrival time at Jupiter is uniquely determined for free-flight trajectories. However, a trajectory speedup or slowdown propulsive maneuver in the vicinity of Jupiter can provide a restricted degree of freedom (plus or minus a few days) to the Jupiter arrival time for fixed Earth and Saturn times. Such a propulsive maneuver can be used to provide time synchronization of the spacecraft for a Jupiter satellite encounter. Variations in the Jupiter arrival point of more than a few hundred kilometers transverse to the free-flight trajectory are prohibited because of the large post-Jupiter propulsive maneuver required to proceed on to Saturn.

The Saturn arrival times are constrained at the early end by the launch vehicle capability and the requirement to stay outside the most intense portions of the Jupiter radiation belts. (Shorter flight times correspond to close Jupiter flybys.) The late Saturn arrival times are constrained by programmatic desires to minimize the total flight time because of reliability concerns and to reduce the large overhead costs of maintaining an operations staff during the long interplanetary cruise phase. For these reasons, the 1977 launches are constrained to arrive at Saturn between September 1980 and the end of 1981. The Saturn arrival point is constrained only by the requirement not to impact the body, rings, or satellites of Saturn.

Within these mission constraints virtually an infinite number of trajectory pairs could be generated. It was the goal of the trajectory selection process to identify a trajectory pair which would be most appropriate for the science investigations and yet be consistent with the mission constraints.

IV. AN OVERVIEW OF THE MJS77 TRAJECTORY SELECTION PROCESS

The management organization for the trajectory selection process is shown in Fig. 3. The Project Science Office was responsible for coordinating the efforts of the scientists and the JPL experiment representatives. The latter are JPL engineers, responsible for the coordination of the science investigations, who report to both the Project Science Office and the science teams. The Mission Analysis and Engineering Manager was responsible for providing technical direction to the JPL trajectory analysts in the generation of trajectories and for the decision analysis. The Project Manager would approve a trajectory pair that had the endorsement of the SSG and the Project Science Office, given the assurance of the Mission Analysis and Engineering Manager that all of the required mission constraints were satisfied.

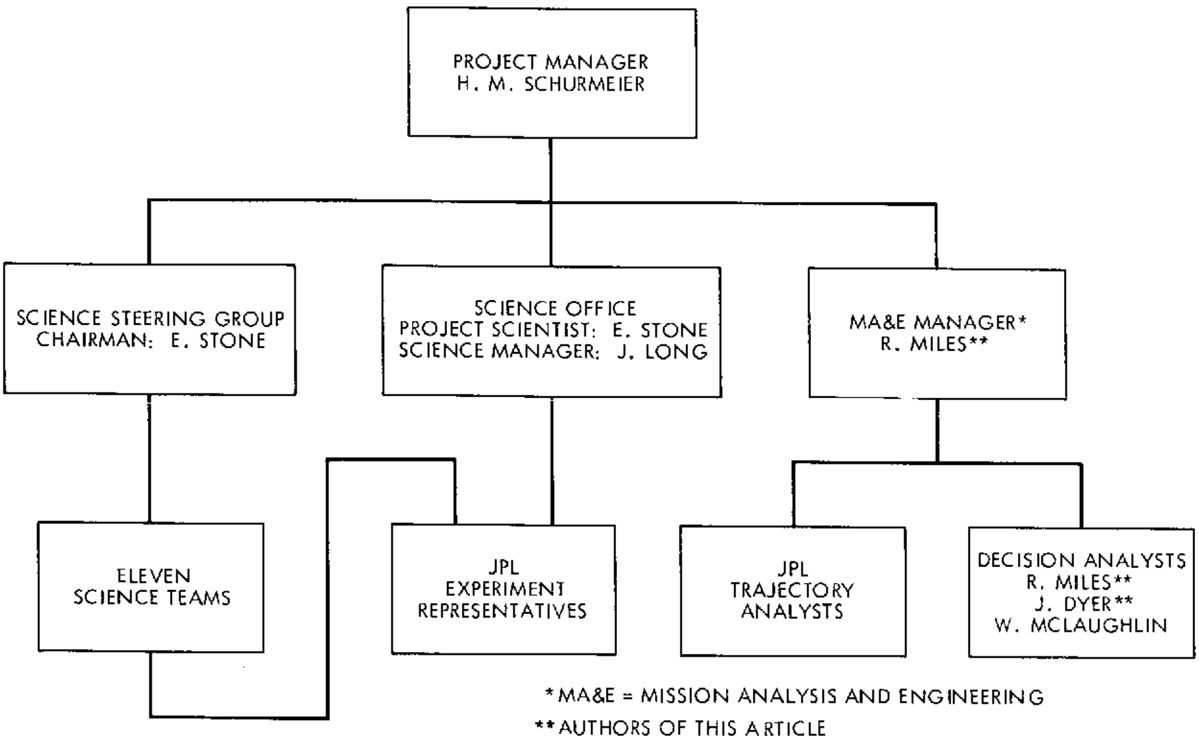

Figure 3. The Management Organization for the MJS77 Trajectory Selection Process.

Guidelines for the MJS77 trajectory selection process were informally established through conversations between the Project Manager, the Project Scientist, and the Mission Analysis and Engineering Manager. These guidelines were:

(1) The process should focus on obtaining a trajectory pair compatible with both the science requirements and the mission constraints.

(2) The process should be compatible with the Project resources allocated for mission analysis. The existing Project management structure and science interfaces should be used.

(3) The process should not divert the efforts of the SSG from other Project activities, nor should it create dissention among the SSG members.

(4) The process should be conceptually simple, and any documentation presented to the SSG should be essentially self-explanatory.

Originally, some consideration was given to developing a multiattributed utility model for the trajectory pairs, with utility-independent attributes. The science teams would have then been requested to assess tradeoffs between the attributes and to assess lotteries over at least one of the attributes, much in the spirit of Keeney (Ref. 8) and others (Refs. 9-11). In principle, it might have been possible to specify an additive or multiplicative utility function for each science team and with these functions to search through the trajectory space and identify preferred trajectory pairs. This was not done for a number of reasons. In the first place, it is not an easy task to identify the appropriate set of utility-independent attributes of a trajectory pair. Even if such sets of attributes exist, they may be different for the different science teams. Further, the level of effort required to identify these attributes for each science team and to construct the utility functions seemed inconsistent with the guideline to develop a conceptually simple process that could be presented to the SSG in a self-explanatory document. Also, the possibility existed that the scientists would be reluctant or unable to provide such detail concerning their preferences at this early stage in the Project. They might feel that the disclosure of this information, even if correctly stated, could prove to be disadvantageous in future negotiations with the Project for resources and in decisions affecting the science investigations.

Several of the science investigations are concerned with information that can only be obtained during satellite encounters. Because the spacecraft-to-satellite geometry can change radically over short periods of time, it was not practical to construct continuous utility functions over the trajectory space for these science teams. Therefore, it was necessary to present the science teams with specifically defined trajectories for their evaluation. Even further, it was necessary to consider trajectory pairs, since the two flights of the mission would not necessarily be utility-independent. Some trajectory pairs might be considered by a science team to provide redundant information, while other trajectory pairs might be complementary in providing unique opportunities.

The process finally endorsed required the JPL engineers to develop, in collaboration with the scientists, a set of candidate trajectory pairs that spanned the range of scientifically attractive alternatives. These candidate trajectory pairs would then be evaluated by each of the science teams. The JPL engineers would then analyze the science team evaluations and present their analysis to the SSG. The final trajectory recommendation would be made by the SSG. Figure 4 shows a flowchart for this process, with a display of the documentation resulting from each stage.

V. THE DEVELOPMENT OF THE CANDIDATE TRAJECTORY PAIRS

The difficulty of developing a set of candidate trajectory pairs stemmed from two factors: (1) the problem of developing trajectories which spanned the range of feasible alternatives, and (2) the problem of identifying trajectory pairs which would meet the requirements of all the science teams. A two-way information exchange was necessary to overcome this difficulty. The JPL engineers determined the characteristics and constraints of the feasible trajectories, and transmitted this information to the science teams (Refs. 12 and 13). Simultaneously, the individual science teams documented their science investigation objectives and the performance characteristics of their instruments (Refs. 14 and 15). Through this information exchange and subsequent direct interaction, the most important science criteria for the trajectories were developed (Ref. 16):

At Jupiter:

(1) Penetration of the Jupiter magnetic flux tube associated with the Galilean satellite Io with a range to Io of less than 40,000 km.

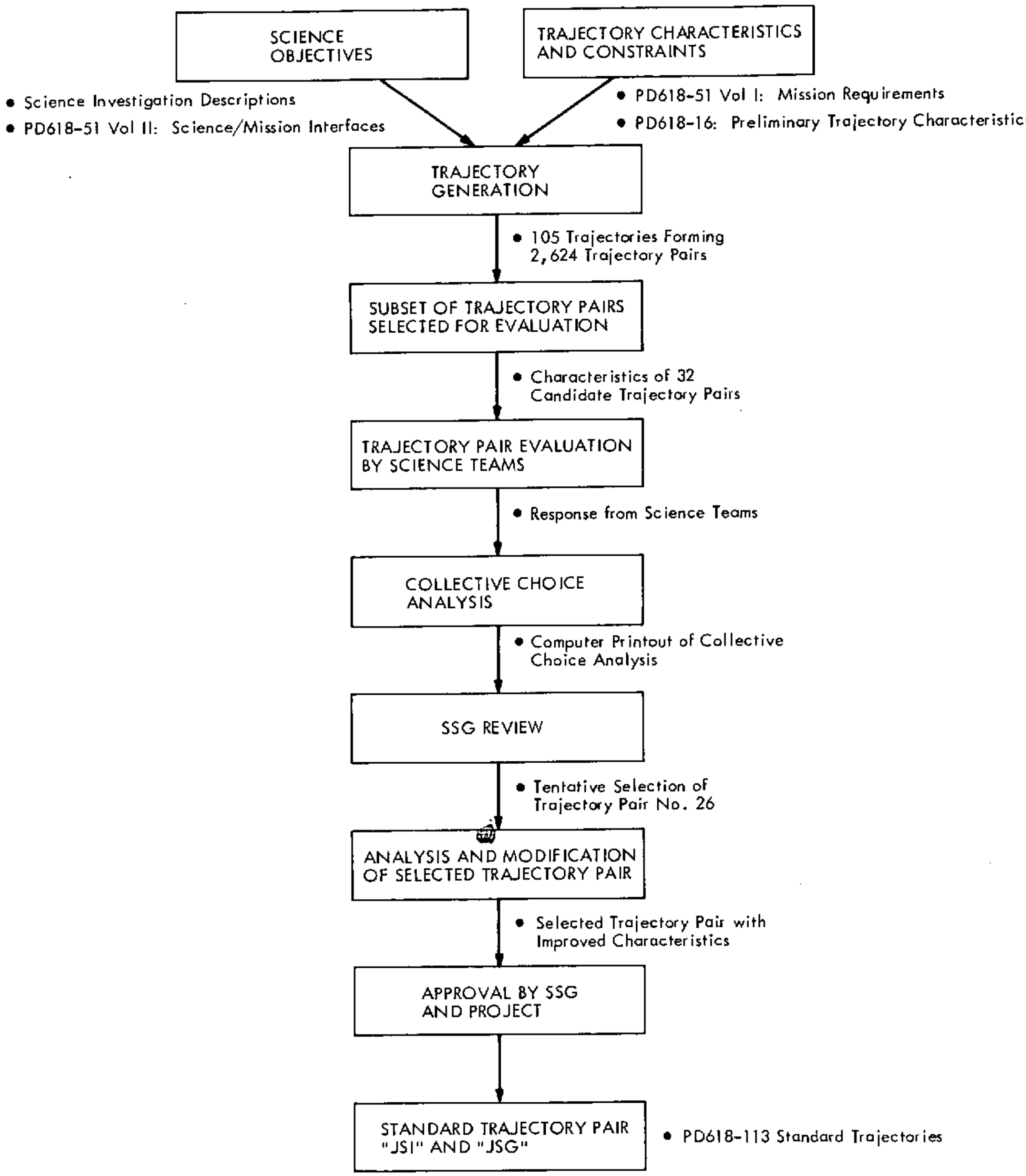

Figure 4. Flow Chart for the MJS77 Trajectory Selection Process.

(2) Close encounter of less than 50,000 km range with at least one Galilean satellite other than Io.

(3) Occultation of the spacecraft by Jupiter with respect to both the Sun and Earth.

At Saturn:

(1) A Titan encounter of less than 50,000 km range with both Sun and Earth occultation.

(2) Multiple satellite encounters of less than 100,000 km range.

(3) Occultation of the spacecraft by Saturn with respect to both the Sun and Earth.

(4) Occultation of the spacecraft by the rings of Saturn with respect to both the Sun and Earth.

(5) Escape from the solar system in the direction of the Sun's motion through interstellar space.

Needless to say, the priority ranking of these general criteria varied from team to team. Since some of the criteria are mutually incompatible on any single trajectory, the majority of them can be satisfied only by considering a pair of complementary trajectories. Nevertheless, a strategy of achieving the maximum number of criteria through the pairing of complementary trajectories was not endorsed by all the science teams. One science team expressed a preference for achieving the most important criteria in a redundant manner on both trajectories in order to maximize the probability of achieving these criteria. Thus differences in preferences for trajectory pairs could be expected between teams, even with compatible criteria, if their strategies with respect to redundancy differed.

Using these science criteria as guidelines, JPL engineers developed a total of 105 single trajectories (Ref. 17). The trajectories were developed by considering free-flight trajectories which departed from Earth on the required launch day and encountered Saturn on the desired arrival day. The trajectories were then varied plus or minus a few days at Jupiter to obtain the most preferred geometries with respect to Jupiter satellite encounters. These trajectories corresponded to the most probable launch days (the opening of the launch period and approximately 11 days later) and covered every feasible Titan arrival opportunity at Saturn from November 1980 to September 1981. In addition, every feasible Iapetus (the second most interesting satellite at Saturn) arrival opportunity was covered, as well as several multiple satellite opportunities at Saturn which could be retargeted to Titan as late as 90 days prior to Saturn arrival.

All of these trajectories were designed to comply with the major constraints of the mission: launch vehicle capability, total flight time, Jupiter closest approach, and navigation capability. The goal was to factor into the trajectories all of the mission constraints, so that the selection criteria could be based solely on the preferences of the science teams. While this goal was not completely achieved, e.g., the Project preferred arrival dates at Saturn prior to June 1981 for cost considerations, it was achieved for all trajectory pairs ranked high in the evaluation.

From these 105 single trajectories, candidate trajectory pairs were then assembled by picking one trajectory corresponding to the opening of the launch period and one trajectory to be launched about 11 days later. A total of 2624 trajectory pairs could be assembled from the 105 single trajectories.

An additional mission constraint was introduced at this point which reduced the possible number of trajectory pairs by roughly a factor of 2. The mission constraint required the Jupiter encounter dates of the two trajectories to be separated by more than one month and the Saturn encounter dates to be separated by less than five months. It is desirable to separate the two Jupiter encounters by more than one month to avoid overloading the data retrieval capabilities of the mission operations. At the other extreme, the costs of maintaining the mission operations in the encounter configuration for many months become very large. Nevertheless, a few trajectory pairs not meeting this mission constraint but having unique characteristics not duplicated in other trajectory pairs were retained for consideration. None of these were ultimately ranked high in the evaluation.

The selection of the set of candidate trajectory pairs was an iterative process, with an initial set being proposed by the JPL engineers, and successive iterations with the science teams resulting in the addition and deletion of candidate trajectory pairs. The number of trajectory pairs that were current candidates at any time varied from 12 to 40. The desire to include trajectory pairs spanning the widest range of alternatives was necessarily tempered by the requirement to keep the total number at a manageable level.

A report was distributed to the science teams which contained trajectory information and instructions for the trajectory pair evaluation (Ref. 18). The trajectory information consisted of tabulated data on the 105 single trajectories and a set of 24 candidate trajectory pairs which had been selected in a series of meetings between the JPL trajectory analysts and the JPL experiment representatives.

The instructions first proposed that the science teams extend the candidate list of 24 trajectory pairs by adding trajectory pairs constructed from the list of 105 single trajectories. Additional trajectory pairs were submitted by the science teams and were then reviewed by the JPL experiment representatives. In this manner, 12 additional trajectory pairs were added to the candidate list, and four on the original list of 24 were dropped when no science team expressed an interest in them. No new single trajectories were added to the original list of 105. The list that was finally used in the evaluation by the science teams contained 32 trajectory pairs, numbered 1 through 36 with four deletions (Ref. 19). This set of 32 candidate trajectory pairs will be denoted as

$$T = \Big\{ \{1, 2, \ldots, 36\} - \{6, 12, 14, 16\} \Big\}.$$

VI. THE SCIENCE TEAM EVALUATIONS OF THE CANDIDATE TRAJECTORY PAIRS

The instructions stated two goals for the trajectory pair evaluation by the science teams: "The first is to suggest procedures for trajectory pair examination which will assist each science team in gaining an in-depth knowledge (of its preferences). The second goal is to ... provide a language of preference which will facilitate communication ... between the teams."

As the first step in the trajectory pair evaluation, the science teams were requested to ordinally rank, in order of decreasing preference, the set T of 32 candidate trajectory pairs. The result of this step was a set of rankings $(t^i_1, \ldots, t^i_{32})$ by each science team $(i = 1, \ldots, 10)$, where $t^i_1 \epsilon T$ denotes the ith science team's most-preferred trajectory pair and $t^i_{32} \epsilon T$ its least-preferred trajectory pair.

The next part of the instructions presented the procedure for determining the preferences of the science teams on a cardinal scale of measurement. Cardinalization of preference was desired in order to measure the strength of preference between trajectory pairs and also to permit the use of collective choice rules requiring measurements on at least an interval scale. This cardinalization was attained through the use of utility function values operationally determined by von Neumann-Morgenstern lotteries (Ref. 20). Since the trajectory pairs were not being evaluated in a risk context, in principle other methods of cardinalization could have been employed (Ref. 21, pp. 92-99). The von Neumann-Morgenstern utility theory was used because of its theoretical consistency, wide acceptance, and ease of implementation.

The utility function values were generated in a two-step process. For the cardinalization of preferences between trajectory pairs, each trajectory pair t_j^i was compared to a lottery between the most-preferred and least-preferred trajectory pairs. The ith science team was requested to assign a probability number p_j^i such that it was indifferent as to whether it received the trajectory pair t_j^i for sure, or the lottery which yielded the most-preferred trajectory pair t_1^i with probability p_j^i or the least-preferred trajectory pair t_{32}^i with probability $1 - p_j^i$. The utility formula corresponding to the cardinalization lottery is

$$u^i(t_j^i) = p_j^i u^i(t_1^i) + (1-p_j^i)\, u^i(t_{32}^i) \tag{1}$$

where $u^i(t_j^i)$ is the utility function value of trajectory pair t_j^i for the ith science team. In this manner each of the 10 science teams generated 32 probability numbers p_j^i, one for each of the 32 trajectory pairs.

It was recognized that the relative strength of preference between the least-preferred trajectory pair and the most-preferred trajectory pair could vary considerably from team to team. Some science investigations are relatively insensitive to the trajectory geometry, and these science teams could be expected to be somewhat indifferent between the trajectory pairs. Other science investigations are much more sensitive to the trajectory geometry, and these science teams could be expected to express strong preferences for certain trajectory pairs. Thus some means of obtaining interteam comparability between science teams for their least-preferred trajectory pairs would be required.

For this normalization each of the science teams was requested to state a probability number $p_\emptyset^i$ such that it was indifferent as to whether it received the least-preferred trajectory pair t^i_{32} for sure, or the lottery which yielded the most-preferred trajectory pair t^i_1 with probability p^i_ϕ or a "no-data" trajectory pair t_ϕ with probability $1-p^i_\phi$. The utility formula corresponding to the normalization lottery is

$$u^i(t^i_{32}) = p^i_\phi u^i(t^i_1) + (1-p^i_\phi)\, u^i(t_\phi). \tag{2}$$

The "no-data" trajectory pair t_ϕ corresponded to a trajectory pair for which the science teams would obtain no data. In the instructions this trajectory pair was called the "Atlantic Ocean Special," in remembrance of the flight of Mariner 8, which terminated abruptly in the Atlantic Ocean.

The scientists were then requested to calculate utility function values for the trajectory pairs with an equation which can be derived from Eqs. (1) and (2) and the utility scaling assumptions that $u^i\,(t^i_1) = 1.0$ and $u^i(t_\phi) = 0.0$ (Fig. 5). The formula for calculating the utility function values for the trajectory pairs thus becomes

$$u^i(t^i_j) = p^i_j + (1-p^i_j)p^i_\phi. \tag{3}$$

The instructions also included a numerical example for the trajectory pair evaluation, a procedure for checking the internal consistency of the preference assignments, a request for the science teams to list the trajectory pair attributes that were most relevant to their evaluation, and a short bibliography on decision analysis.

The science teams were given approximately one month to carry out this procedure. When the evaluation data from the 10 science teams were received by the JPL engineers for analysis, it was immediately evident that the normalization lottery for interteam comparison had not achieved the desired result. The Project Scientist believed that some of the science teams had assigned utility function values to the least-preferred trajectory pairs which were much too high, while others were much too low. An attempt to negotiate revised utility function values for the least-preferred trajectory pairs was only partially successful. The final values assigned by the science teams to the least-preferred trajectory pairs ranged from 0.101 to 0.800. The ordinal rankings and the cardinal utility function values which resulted from this negotiation are shown in Table II.

Several science teams were extremely risk-averse. The duration of the MJS77 Project is about 10 years and may represent the only foreseeable

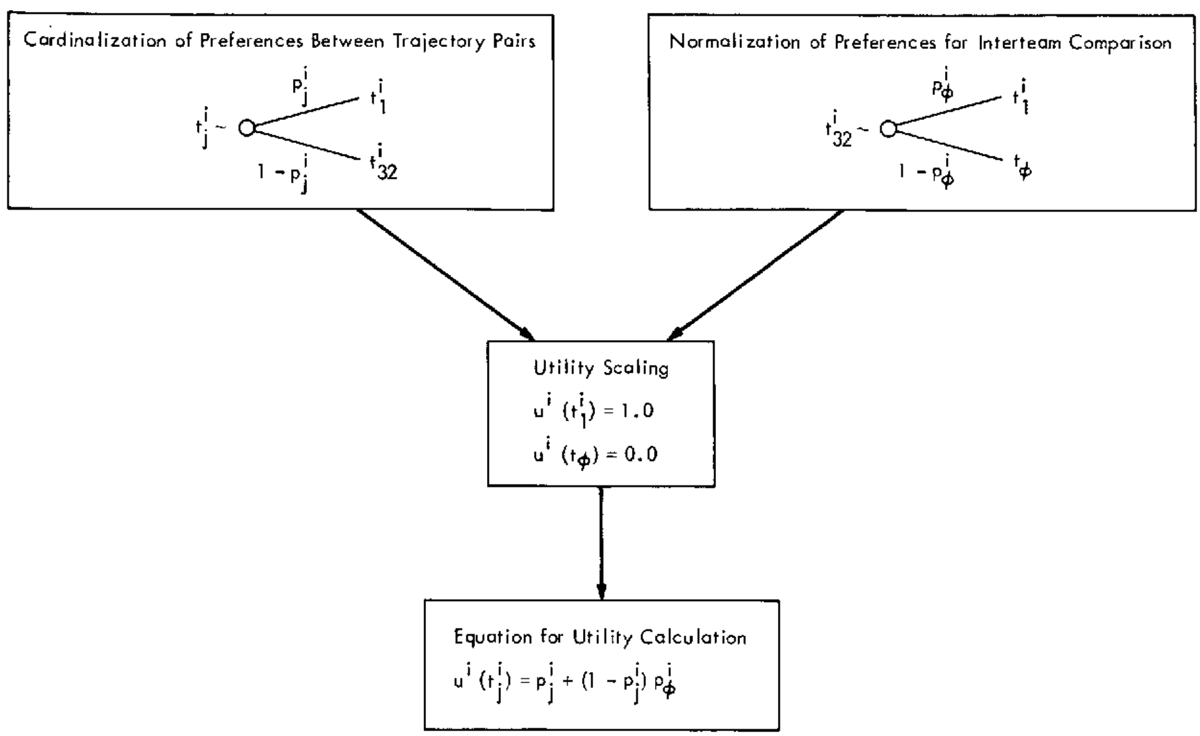

Figure 5. The Generation of the Cardinal Utility Function Values.

Table II

The Science Team Ordinal Rankings and Cardinal Utility Function Values

TRAJECTORY PAIR	RSS		IRIS		ISS		PPS		UVS		CRS		LECP		MAG		PLS		PRA	
	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY	RANK	UTILITY
1	6.0	0.772	28.0	0.871	13.5	0.850	22.0	0.550	17.0	0.820	24.5	0.850	14.0	0.700	15.0	0.500	26.5	0.600	19.0	0.546
2	6.0	0.772	24.5	0.875	22.0	0.750	25.0	0.530	22.0	0.790	5.5	0.910	7.0	0.830	19.0	0.480	11.0	0.750	18.0	0.547
3	20.5	0.600	14.5	0.925	4.0	0.960	28.5	0.520	5.0	0.910	28.5	0.840	28.0	0.450	27.5	0.350	7.0	0.900	24.0	0.109
4	20.5	0.600	6.0	0.948	26.0	0.700	20.0	0.570	2.0	0.970	28.5	0.840	27.0	0.480	26.0	0.351	7.0	0.900	25.0	0.108
5	20.5	0.600	9.0	0.943	28.5	0.670	17.0	0.600	4.0	0.920	13.0	0.880	6.0	0.900	6.0	0.800	1.5	1.000	6.0	0.600
7	20.5	0.600	32.0	0.750	32.0	0.600	32.0	0.500	18.0	0.810	32.0	0.800	30.0	0.430	25.0	0.360	26.5	0.600	26.0	0.107
8	20.5	0.600	20.0	0.886	10.0	0.900	5.0	0.780	13.5	0.830	21.0	0.860	11.0	0.740	7.0	0.700	17.5	0.700	9.0	0.556
9	20.5	0.600	12.0	0.930	16.0	0.800	13.0	0.650	26.0	0.760	9.5	0.890	19.0	0.610	16.0	0.490	17.5	0.700	13.0	0.552
10	3.0	0.887	11.0	0.935	24.0	0.720	8.5	0.720	19.5	0.800	2.0	0.960	20.0	0.600	24.0	0.400	17.5	0.700	7.0	0.558
11	20.5	0.600	13.0	0.928	7.0	0.920	3.5	0.810	28.5	0.720	5.5	0.910	26.0	0.490	31.0	0.260	32.0	0.500	27.0	0.106
13	8.0	0.652	18.0	0.915	22.0	0.750	28.5	0.520	13.5	0.830	31.0	0.810	31.0	0.320	30.0	0.280	26.5	0.600	28.0	0.105
15	3.0	0.887	29.5	0.869	16.0	0.800	18.5	0.580	9.0	0.840	17.5	0.870	16.0	0.650	20.0	0.430	11.0	0.750	22.0	0.543
17	20.5	0.600	4.0	0.966	13.5	0.850	6.5	0.750	13.5	0.830	24.5	0.850	9.0	0.770	14.0	0.510	17.5	0.700	8.0	0.557
18	20.5	0.600	8.0	0.944	10.0	0.900	15.0	0.630	22.0	0.790	13.0	0.880	24.0	0.560	17.5	0.485	26.5	0.600	29.0	0.104
19	20.5	0.600	26.5	0.873	10.0	0.900	28.5	0.520	26.0	0.760	13.0	0.880	25.0	0.500	29.0	0.300	26.5	0.600	30.0	0.103
20	6.0	0.772	10.0	0.937	31.0	0.620	22.0	0.550	32.0	0.630	21.0	0.860	22.0	0.580	27.5	0.350	26.5	0.600	16.0	0.549
21	20.5	0.600	14.5	0.925	3.0	0.970	31.0	0.510	22.0	0.790	28.5	0.840	29.0	0.440	11.0	0.575	7.0	0.900	31.0	0.102
22	20.5	0.600	29.5	0.869	10.0	0.900	18.5	0.580	31.0	0.640	5.5	0.910	17.0	0.630	23.0	0.405	26.5	0.600	23.0	0.542
23	20.5	0.600	24.5	0.875	16.0	0.800	25.0	0.530	30.0	0.670	5.5	0.910	8.0	0.780	22.0	0.408	26.5	0.600	20.0	0.545
24	3.0	0.887	17.0	0.919	26.0	0.700	28.5	0.520	1.0	1.000	28.5	0.840	32.0	0.300	32.0	0.250	26.5	0.600	32.0	0.101
25	20.5	0.600	7.0	0.947	28.5	0.670	25.0	0.530	9.0	0.840	1.0	0.970	5.0	0.960	5.0	0.950	11.0	0.750	1.0	1.000
26	20.5	0.600	2.0	0.996	10.0	0.900	11.0	0.700	7.0	0.850	17.5	0.870	3.0	0.980	1.0	1.000	1.5	1.000	2.0	0.990
27	20.5	0.600	1.0	1.000	30.0	0.650	16.0	0.610	3.0	0.930	17.5	0.870	1.0	1.000	4.0	0.970	4.0	0.950	3.0	0.980
28	1.0	1.000	23.0	0.876	26.0	0.700	14.0	0.640	13.5	0.830	24.5	0.850	13.0	0.720	17.5	0.485	11.0	0.750	11.0	0.554
29	20.5	0.600	5.0	0.957	19.0	0.770	6.5	0.750	9.0	0.840	3.0	0.930	2.0	0.990	2.0	0.990	4.0	0.950	4.0	0.970
30	20.5	0.600	22.0	0.878	1.0	1.000	12.0	0.690	26.0	0.760	17.5	0.870	10.0	0.750	21.0	0.420	17.5	0.700	12.0	0.553
31	20.5	0.600	3.0	0.987	5.0	0.940	8.5	0.720	6.0	0.860	8.0	0.900	4.0	0.975	3.0	0.980	4.0	0.950	5.0	0.960
32	20.5	0.600	19.0	0.890	19.0	0.770	22.0	0.550	28.5	0.720	13.0	0.880	18.0	0.620	13.0	0.570	17.5	0.700	14.0	0.551
33	20.5	0.600	26.5	0.873	6.0	0.930	10.0	0.710	19.5	0.800	9.5	0.890	21.0	0.590	12.0	0.573	17.5	0.700	15.0	0.550
34	20.5	0.600	16.0	0.921	19.0	0.770	3.5	0.810	13.5	0.830	21.0	0.860	15.0	0.670	8.0	0.600	11.0	0.750	17.0	0.548
35	20.5	0.600	21.0	0.883	2.0	0.980	2.0	0.820	13.5	0.830	13.0	0.880	12.0	0.730	9.0	0.595	17.5	0.700	10.0	0.555
36	20.5	0.600	31.0	0.813	22.0	0.750	1.0	1.000	24.0	0.770	24.5	0.850	23.0	0.570	10.0	0.594	26.5	0.600	21.0	0.544

opportunity for some of these scientists to be involved in a planetary mission. Given this situation, it was very difficult for them to consider the "no-data" trajectory pair with a significant, nonzero probability. One science team responded initially that they would only accept a probability of less than 0.001 of obtaining the "no-data" trajectory pair, so that their utility function values for candidate trajectory pairs covered the "... remarkable range of 1.0 to 0.999..." Voicing a similar concern, the JPL experiment representative for a second science team stated that "... the utility values indicate, in my opinion, that the team lacks a gambling nature, not that the pairs are of approximately equal value to our experiment; i.e., the utilities serve more as a group Rorschach test than as a useful gauge to scientific judgments."

The utility function values assigned to the least-preferred trajectory pairs which were very low could be explained in terms of gaming. The science teams recognized that the maximum effect on the collective choice rules could be obtained by biasing these utility assignments downward. By spreading the utility function values for the candidate trajectory pairs over the entire range of [0.0, 1.0] rather than, say, over [0.8, 1.0], a science team would obviously have more influence on a collective choice rule which multiplies together the utility function values of all the science teams. In retrospect, it probably was not appropriate to request the science teams to evaluate the normalization lottery, thus in effect handicapping themselves.

Two coalitions of science teams were formed during the evaluation process, one consisting of the fields and particles science investigations (CRS, LECP, MAG, PLS, and PRA) and the other of the platform-mounted science investigations (IRIS, ISS, PPS, and UVS). Table III shows the results of a statistical test for agreement among these coalitions. Kendall's coefficient of concordance W (Ref. 22) uses the ordinal rankings of the science teams to measure agreement on a scale from 0.0 to 1.0, where 0.0 implies complete disagreement and 1.0 implies complete agreement. For the total SSG, W = 0.30, which is significant at the 0.001 level for 10 teams. For the fields and particles coalition, whose science objectives are mutually related – investigations of phenomena interrelated by Maxwell's equations of electromagnetism on a cosmic scale – W = 0.63, which is significant at the 0.001 level for five teams. For the platform-mounted science coalition, whose science objectives are not as closely related, W = 0.33, which is not significant at the 0.05 level for four teams.

Table III

A Statistical Test for Agreement Within Groups

W = KENDALL'S COEFFICIENT OF CONCORDANCE
DEGREES OF FREEDOM = 31

GROUP	NUMBER OF TEAMS	W	LEVEL OF SIGNIFICANCE
SSG	10	0.30	<0.001
FIELDS AND PARTICLES COALITION	5	0.63	<0.001
PLATFORM-MOUNTED SCIENCE COALITION	4	0.33	~ 0.1

The coalitions were important to the science teams, both for understanding which trajectory pairs were likely to receive endorsement and for developing new, mutually satisfactory trajectory pairs. The fields and particles coalition met once at the Goddard Space Flight Center, Greenbelt, Maryland, on October 10, 1973. The platform-mounted science coalition and Radio Science met once at Stanford University on October 11, 1973. There is no evidence that the coalitions had an undesirable effect on the selection process.

VII. THE COLLECTIVE CHOICE ANALYSIS

After the trajectory pair evaluation data had been received from all 10 of the science teams, a collective choice analysis was performed at JPL. In selecting the science teams to participate on the mission, NASA had made no priority assignments, preferring that conflicts be resolved as they arose rather than by a preassigned rule. Thus, since no single collective choice rule could be invoked, the trajectory pairs were ordered according to several rules, each with a different underlying rationale. The collective choice rules selected for consideration were the rank sum rule utilizing the ordinal rankings, and the additive rule, the multiplicative rule, and the maximin rule utilizing the cardinal utility function values.

The rank sum rule is one of the oldest and most widely used. It requires the calculation of the mean ordinal rank for each trajectory pair, with the trajectory pair achieving the lowest mean rank being most preferred. It is a slight variation of the Borda method, wherein each individual assigns a "mark" to the $\underline{n}$ alternatives (ranked from worst to best) of 0, 1, . . . , n-1, and the winner is the alternative receiving the largest total number of "marks" (Ref. 23). An undesirable feature of this rule is that arithmetic operations are being performed on ordinal data. Nevertheless, it does have the virtue of simplicity, it requires only ordinal responses from the science teams, and it is easily understood.

The additive collective choice rule defined on the cardinal utility function values can be written in the general form

$$C(t_k) = \sum_{i=1}^{10} \lambda^i u^i(t_k) \qquad (4)$$

where $k \epsilon T$ denotes a particular trajectory pair, and λ^i is a weighting factor for the ith science team.

The following sufficient conditions for an additive collective choice rule have been given by Harsanyi (Ref. 24):

Condition 1: Collective choice satisfies the postulates of utility theory (specifically, postulates I, II, III, and IV of Marschak (Ref. 25)).

Condition 2: Individual preferences satisfy these same postulates.

Condition 3: If two alternatives are indifferent from the standpoint of every individual, they are indifferent from a collective choice standpoint.

The intuitively appealing "reasonableness" of these conditions argues in favor of the additive form. Harsanyi (Ref. 24) has discussed the ethical justification of this form of collective choice. For comments and caveats, see Sen (Ref. 21, pp. 89-104, 131-151). Nevertheless, there still remains the difficult problem of making interteam utility comparisons. This problem requires consideration of the related issues of the interteam normalization through the scaling of each science team's utility function and the choice of the λ^i's, the weighting factors.

The multiplicative collective choice rule is based on the Nash Bargaining Model with a restricted bargaining set of pure strategies. The Nash Bargaining Model is one specific interpretation of a "fair" solution to a bargaining problem (Refs. 26 and 27). The axioms of fairness postulated by Nash are the following:

Axiom 1: Invariance with respect to utility transformations.

Axiom 2: Pareto optimality.

Axiom 3: Independence of irrelevant alternatives.

Axiom 4: Symmetry.

The Nash solution maximizes the product of the increase in the utility function values which the participants gain with respect to a "status quo." The status quo is the alternative which the participants receive if they cannot achieve a mutually acceptable bargain. The use of the Nash Bargaining Model with a restricted bargaining set of pure strategies has been explored by

Bonnardeaux, Dolait, and Dyer (Ref. 28). The conclusion of their efforts was that this model could provide useful information, particularly if the status quo alternative is chosen appropriately. Loosely speaking, an individual given a comparative advantage in the status quo will maintain an advantage in the Nash solution to the bargaining problem. In this spirit the "no-data" trajectory pair was selected as the status quo for all science teams. Since for the "no-data" trajectory pair $u^i(t_\emptyset) = 0.0$ for all science teams, the general form of the multiplicative collective choice rule is

$$C(t_k) = \left[\prod_{i=1}^{10} u^i(t_k)\right]^{\frac{1}{10}} \tag{5}$$

where $k \epsilon T$.

The maximin collective choice rule, discussed by Rawls (Ref. 29), maximizes the minimum utility function value received by any science team. The maximin rule can be interpreted as another definition of "fairness." Although the maximin rule is simple to apply, the results are extremely sensitive to the interteam normalization assumptions.

The interteam normalization procedure was one of the principal issues of concern in the evaluation of the trajectory pairs. The introduction of the "no-data" trajectory pair $t_\emptyset$ with $u^i(t_\emptyset) = 0.0$ for $i = 1, \ldots, 10$ was an attempt to reconcile the interteam normalization problem by identifying a worst alternative with a common outcome for each science team. In addition, since the science teams were involved in the determination of the candidate set of trajectory pairs, it was assured that at least one trajectory pair would be "very good" for each science team. To this extent, the normalization procedure could be said to be "fair."

However, because of the problem of rationalizing the results of the normalization lottery, two other normalization procedures were also used to test the sensitivity of the collective choice rules to the utility function values assigned to the least-preferred trajectory pairs. The second normalization procedure linearly transformed the utility function values of each science team as shown in Table II into the range [0.0, 1.0], where the value 0.0 was assigned to the least-preferred trajectory pair. The third normalization procedure linearly transformed the utility function values of each science team into a range assigned by the Project Scientist, based on his assessment of the appropriateness of the least-preferred trajectory pair for each science investigation. The Project Scientist assigned the range of $[0.6, 1.0]$ to the encounter-oriented science teams (RSS, IRIS, ISS, PPS, UVS, and PRA), and the range $[0.8, 1.0]$ to the science teams with both cruise and encounter objectives (CRS, LECP, MAG, and PLS).

Another issue was the choice of the weighting factor λ^i for each science team in the additive collective choice rules. Two sets of weighting factors were used: (1) equal weights of $\lambda^i = 1.0$ for all science teams and (2) $\lambda^i = 2.0$ for the encounter-oriented science teams (RSS, IRIS, ISS, PPS, UVS, and PRA) and $\lambda^i = 1.0$ for the other science teams (CRS, LECP, MAG, and PLS). Both sets of weighting factors were readily accepted by the SSG as representative weighting factors for a sensitivity analysis. The first set of weighting factors implies that all science investigations would be of equal importance to the mission, if they could be flown on the trajectory pair most preferred by that science team. No particular justification was made for the allocation of the second set of weighting factors, but plausible arguments would be that either the encounter-oriented science investigations were more important or that these investigations, being more sensitive to the trajectory geometry, should have a greater influence on the trajectory pair selection, although in principle the normalization lottery should have compensated for the sensitivity to trajectory geometry.

The results of the analysis with the various collective choice rules are presented in Table IV. The collective choice rules were scaled to yield values in the range $[0.0, 1.0]$ for ease of comparison. All of the collective choice rules would assign a value of 1.0 to a trajectory pair which was evaluated as the most-preferred trajectory pair by every science team.

The trajectory pair rankings by the rank sum rule are shown in the first data column of Table IV, with the values in the second column being the mean ranks of the science teams linearly transformed into the range $[1/32, 1.0]$, with 1.0 most preferred. The next six collective choice rules are based on the additive form, with the two weighting factor sets times the three normalization procedures accounting for the six middle data columns of Table IV. Finally, the last two collective choice rules are based on the multiplicative rule, with the "no-data" trajectory pair taken as the status quo alternative. The two multiplicative rules differ in that the utility function values for one rule are scaled upward from $u^i(t^i_{32}) = p^i_{\emptyset}$ as assigned by the science teams, and for the

Table IV

The Collective Choice Rankings and Values

COLLECTIVE CHOICE RULE: FORM	RANK SUM		ADDITIVE												NASH			
$u^i(t^i_{32})$			p^i_ϕ		0.0		0.6 OR 0.8		p^i_ϕ		0.0		0.6 OR 0.8		p^i_ϕ		0.6 OR 0.8	
λ^i WEIGHTING			1.0		1.0		1.0		1.0 OR 2.0		1.0 OR 2.0		1.0 OR 2.0					
TRAJECTORY PAIRS	RANK	VALUE	RANK	VALUE	RANK	VALUE	RANK	VALUE	RANK	VALUE	RANK	VALUE	RANK	VALUE	RANK	VALUE	RANK	VALUE
31	1	0.822	2	0.887	1	0.724	1	0.901	1	0.871	1	0.691	1	0.884	1.5	0.877	1	0.892
29	2	0.797	3	0.875	3	0.692	3	0.884	3	0.852	3	0.638	3	0.860	3	0.865	3	0.874
26	3	0.795	1	0.889	2	0.710	2	0.896	2	0.870	2	0.676	2	0.878	1.5	0.877	2	0.886
27	4	0.719	4	0.856	4	0.641	4	0.871	4	0.833	4	0.596	4	0.848	4	0.839	4	0.856
5	5	0.683	6	0.791	6	0.555	8	0.841	6.5	0.765	8	0.502	12	0.813	6	0.776	11	0.829
25	6	0.678	5	0.822	5	0.597	5	0.851	5	0.800	5	0.535	9	0.822	5	0.804	7	0.836
35	7	0.655	7	0.757	8	0.511	6.5	0.846	6.5	0.765	7	0.517	5.5	0.833	8	0.745	6	0.839
17	8	0.622	10	0.738	11	0.475	10.5	0.836	10	0.746	10	0.487	8	0.823	10.5	0.725	9.5	0.830
8	9	0.611	8	0.755	9	0.488	10.5	0.836	8	0.756	11	0.486	10	0.820	7	0.746	9.5	0.830
10	10	0.605	12	0.728	7	0.514	6.5	0.846	11	0.744	6	0.519	5.5	0.833	14	0.706	5	0.843

other rule from $u^i(t^i_{32}) = 0.6$ or 0.8 as assigned by the Project Scientist. The results for the two multiplicative rules are shown in the right-hand data columns of Table IV.

Since the Radio Science Team (RSS) evaluated 24 of the 32 trajectory pairs as "least-preferred," the use of the interteam normalization procedure with $u^i(t^i_{32}) = 0.0$ would have given little useful information in the multiplicative model. Only six trajectory pairs would have received non-zero values from Equation 5. For a similar reason, the maximin rule of Rawls proved not to be useful. With the $p^i_\emptyset$ normalization five trajectory pairs were tied for first ranking (5, 26, 27, 29, and 31); with the 0.0 normalization only six trajectory pairs were ranked (28≻10≻15≻1≻2≻13≻all others); and with the 0.6/0.8 normalization only six trajectory pairs were ranked (10≻28≻15≻1≻2≻13≻all others).

One well-known collective choice rule not included in the JPL analysis was the majority decision rule (Refs. 21 and 30), which can lead to intransitivity and even to violation of a weaker condition, acyclicity. A preference ordering $\succ$ over a set of alternatives $t_k \varepsilon T$ is acyclical if and only if the following holds:

$$\forall \quad t_k \varepsilon T: \quad \left\{ t_1 \succ t_2 \ \& \ t_2 \succ t_3 \ \& \ \ldots \ \& \ t_{k-1} \succ t_k \right\} \rightarrow t_1 \succsim t_k$$

where $\succsim$ implies preference or indifference. The application of the majority decision rule to the 10 trajectory pairs ranked highest by the rank sum rule preserved acyclicity, but did result in two ties, thus forming the following ordering: (26≻{29, 27, 31}≻25≻5≻8≻35≻17≻10) with 29~27, 27~31, and 29≻31. The trajectory pairs ranked in the top four by the majority decision rule were ranked in the top four by all the collective choice rules of Table IV.

The data in Table IV indicate a substantial agreement among the nine collective choice rules presented there. This is partially fortuitous, partially a result of the statistical properties of these rules, and also a result of the generally compatible requirements of the science teams. All of the collective choice rules could be expected to be highly correlated on a statistical basis. Sums and products of random variables are highly correlated, even if the random variables are independent and uniformly distributed over their domain. For example, for independent random variables X_i uniformly distributed over $[0.0, 1.0]$,

$$\frac{1}{10}\sum_{i=1}^{10} X_i$$

and

$$\left[\prod_{i=1}^{10} X_i\right]^{\frac{1}{10}}$$

are correlated with a Pearson correlation coefficient of 0.89. Any positive correlation between the X_i's, i.e., agreement between the science teams, will increase this number. For the 32 candidate trajectory pairs, the additive rule and the Nash rule (with p^i_ϕ normalization and $\lambda^i = 1.0$ weighting) are correlated with a Pearson correlation coefficient of 0.98. Agreement between the nine collective choice rules, as measured by Kendall's coefficient of concordance (Ref. 22), is W = 0.96 for the 32 candidate trajectory pairs.

The generally compatible trajectory requirements of the science teams were to a large degree assured by the detailed project planning activities of JPL and by the coordinated science investigation selection process of NASA. The MJS77 mission design has been derived from earlier work done on the Outer Planets Grand Tour Project (Refs. 31 and 32), and the MJS77 mission definition phase which followed when the Grand Tour Project was reconstituted as the MJS77 Project. A pre-project Science Steering Group participated in both of these activities (Refs. 33 and 34). At the conclusion of these activities NASA formally requested proposals from the science community for science investigations to be performed on the MJS77 mission, with the proviso that, if at all possible, the proposals should be compatible with the spacecraft design and the trajectory characteristics developed during the mission definition phase (Refs. 35 and 36). The degree of compatibility formed part of the science selection criteria. Thus it was not anticipated that the trajectory pair selection process would uncover major unresolvable conflicts between the trajectory requirements of the science teams.

To complete the analysis of Table IV, define the relation $\succ_R$ such that for any $m, n \epsilon T$, $t_m \succ_R t_n$ if and only if $t_m \succ_r t_n$ for all $r = 1, \ldots, 9$ where $\succ_r$ corresponds to the ordering determined by the $r\underline{th}$ collective choice rule of Table IV. The relation $\succ_R$ determines three equivalence classes among the 10 trajectory pairs of Table IV, such that

$$\{31,\ 29,\ 26\} \succ_R \{27\} \succ_R \{5,\ 25,\ 35,\ 17,\ 8,\ 10\}.$$

Thus, if the science teams were able to accurately express their preferences over the candidate trajectory pairs, and if the collective choice rules were appropriate, then the selected trajectory pair should be a member of the set $\{31,\ 29,\ 26\}$.

VIII. THE SCIENCE STEERING GROUP MEETING

Following the science team evaluation and the JPL analysis of the candidate trajectory pairs, the SSG selected the science-preferred trajectory pair at the October 22 and 23, 1973 SSG meeting (Refs. 37 and 38). The afternoon of the first day began with a discussion of the general trajectory requirements of the science investigations. The JPL experiment representatives summarized the trajectory characteristics required by each science team, and a JPL trajectory analyst summarized the general compatibilities and incompatibilities of these trajectory requirements. After an hour it became evident that the trajectory pair selection could not be made on the basis of this discussion. While the discussion did clarify the trajectory requirements of the individual science teams, no rationale emerged for trading off incompatible requirements, and no means was found for moving from the general trajectory requirements to the selection of a specific trajectory pair. At this point the SSG requested that JPL present the collective choice analysis.

The Mission Analysis and Engineering Manager first reviewed the requirements and constraints which influenced the selection of the candidate trajectory pairs. The JPL trajectory analyst described the trajectory characteristics of the trajectory pairs ranked highest by the collective choice rules. The Mission Analysis and Engineering Manager then described the rationale of each of the collective choice rules, and presented a summary of the collective choice analysis as shown in Tables IV and V. Table V shows the science team ordinal rankings for the 10 trajectory pairs ranked highest by the rank sum collective choice rule.

Two observations which can be made from Tables IV and V are of primary importance. First, Trajectory Pairs 31, 29, and 26 are ranked in the top three by all the collective choice rules. In the ensuing discussion, the majority of the SSG expressed a preference for one of these three trajectory pairs. Second, the Radio Science Team (RSS) considered any trajectory pair ranked high by the collective choice rules to be undesirable. The Radio Science Team strongly preferred a trajectory pair with one trajectory which would be occulted at Saturn along the major axis of Saturn's rings, in this manner yielding a complete radio attenuation profile of the ring structure. The JPL trajectory analyst stated that it would be possible to improve somewhat the ring occultation geometry without degrading the Saturn secondary satellite encounters, but that an optimum ring occultation and a good Titan encounter were mutually

Table V

The Science Team Ordinal Rankings for Preferred Trajectory Pairs

		COLLECTIVE CHOICE RANKING		SCIENCE TEAM ORDINAL RANKINGS									
		RANK SUM	ADDITIVE $u^i\ (t^i_{32}) = p^i_\phi;\ \lambda^i = 1.0$	RSS	IRIS	ISS	PPS	UVS	CRS	LECP	MAG	PLS	PRA
TRAJECTORY PAIRS	31	1	2	20.5	3.0	5.0	8.5	6.0	8.0	4.0	3.0	4.0	5.0
	29	2	3	20.5	5.0	19.0	6.5	9.0	3.0	2.0	2.0	4.0	4.0
	26	3	1	20.5	2.0	10.0	11.0	7.0	17.5	3.0	1.0	1.5	2.0
	27	4	4	20.5	1.0	30.0	16.0	3.0	17.5	1.0	4.0	4.0	3.0
	5	5	6	20.5	9.0	28.5	17.0	4.0	13.0	6.0	6.0	1.5	6.0
	25	6	5	20.5	7.0	28.5	25.0	9.0	1.0	5.0	5.0	11.0	1.0
	35	7	7	20.5	21.0	2.0	2.0	13.5	13.0	12.0	9.0	17.5	10.0
	17	8	10	20.5	4.0	13.5	6.5	13.5	24.5	9.0	14.0	17.5	8.0
	8	9	8	20.5	20.0	10.0	5.0	13.5	21.0	11.0	7.0	17.5	9.0
	10	10	12	3.0	11.0	24.0	8.5	19.5	2.0	20.0	24.0	17.5	7.0

exclusive. A general concern was expressed by the SSG that any improvement to the ring occultation geometry should not significantly degrade the secondary satellite encounters.

The team leader of the Imaging Science Investigation (ISS) expressed a dislike for Trajectory Pair 29, to which they had assigned an ordinal ranking of 19 and a utility function value of 0.770, but indicated that either Trajectory Pair 31 or 26 would be acceptable (utility function values of 0.940 and 0.900). The team leader of the Cosmic Ray Investigation (CRS) stated that they could accept Trajectory Pair 26 which, even though ordinally ranked at 17.5, was given a utility function value of 0.870 (compared to 0.900 for Trajectory Pair 31). The team leader of the Radio Science Investigation (RSS) expressed a preference for Trajectory Pair 26 over Trajectory Pair 31, since Trajectory Pair 26 did give at least a partial ring occultation. This prompted some discussion on the part of the SSG to the effect that if the Radio Science Team really did have a preference for Trajectory Pair 26 over Trajectory Pair 31, then why was this not reflected in their utility function values? See Table VI for the RSS, ISS, and CRS ordinal rankings and utility function values supporting this discussion. The other team leaders expressed their satisfaction with either Trajectory Pair 31 or 26.

On the basis of this discussion, Trajectory Pair 26 was tentatively selected as the science-preferred trajectory pair. The JPL trajectory analysts worked that night to improve the ring occultation geometry of Trajectory Pair 26 without degrading the secondary satellite encounters. This analysis was presented to the SSG the following morning and met with approval. Following the SSG meeting, one further change was made to the selected trajectory pair. This change improved the satellite encounters while retaining essentially the same ring occultation geometry. The possibility remains that had Trajectory Pair 31 been improved in the same manner as Trajectory Pair 26, it might have emerged as the science-preferred trajectory pair.

The modified version of Trajectory Pair 26 was approved by the Project Manager, and was documented as the MJS77 "Standard Trajectories" (Ref. 39). The two individual trajectories were labeled "JSI" and "JSG," where JS stands for Jupiter/Saturn, and I and G stand for the two Jupiter satellites Io and Ganymede, which are encountered on the corresponding trajectories.

Table VI

RSS, ISS, and CRS Evaluation of Three Trajectory Pairs

TRAJECTORY PAIRS	RSS		ISS		CRS	
	RANK	VALUE	RANK	VALUE	RANK	VALUE
31	20.5	0.600	5.0	0.940	8.0	0.900
29	20.5	0.600	19.0	0.770	3.0	0.930
26	20.5	0.600	10.0	0.900	17.5	0.870

IX. THE SCIENCE TEAM QUESTIONNAIRE

After the selection of JSI and JSG as the Project standard trajectory pair, a questionnaire on the trajectory selection process was mailed to the members of the SSG. Nine of the 10 science teams responded to the questionnaire. In some cases the questionnaire was filled out by the science team leader, in other cases it was discussed by the entire science team, and in still others it was filled out by the JPL experiment representative after consultation with the science team leader.

The questionnaire contained 18 questions, each requiring a response on a scale from -5 to +5. Depending on the specific question, a response of -5 corresponded to "no," "not useful," "very bad," or "very unfair," while a +5 corresponded to "yes," "very useful," "very good," or "very fair."

The responses to the questionnaire are given in Table VII, where the left-hand column contains an abbreviated version of the questions actually posed. The next column gives the median response of the science teams. The science teams and their responses are given on the right and identified by number rather than by name to preserve confidentiality.

The responses of Science Team 3 warrants an initial comment. Science Team 3 strongly felt that the concept of achieving complementary objectives on the two trajectories was incorrect. This science team preferred two redundant trajectories to maximize the probability of achieving the most important objectives. Thus their principal objection to the trajectory selection process was that the wrong alternatives were being evaluated. In a letter to the Project Science Office they stated:

> "The ... team feels that the current concept of two independent trajectories is not basic to the mission. The second spacecraft should be considered principally as a backup to the first until the success of the first is assured. The science return from the first spacecraft should be maximized. The utility analysis should be applied (only) to this first mission."

For most questions the inclusion of the responses from Science Team 3 makes no significant difference in the median response. Only in Question 9 does it change the median response by as much as two units.

Table VII

Responses from the Science Team Questionnaire

QUESTIONS	MEDIAN RESPONSE	SCIENCE TEAMS								
		#1	#2	#3	#4	#5	#6	#7	#8	#9
1. DID THE PROCESS OF ORDINALLY RANKING THE TRAJECTORY PAIRS AID YOUR UNDERSTANDING OF THEM?	+5	+5	+4	-5	+5	+5	+3	+4	+5	+5
2. WERE THE ORDINAL RANKINGS A USEFUL WAY TO COMMUNICATE YOUR PREFERENCES?	+3	0	+3	-5	+5	+4	-2	+4	0	+5
3. DID THE ASSIGNMENT OF CARDINAL UTILITY VALUES INCREASE YOUR UNDERSTANDING OF THE PAIRS <u>BEYOND</u> WHAT RESULTED FROM THE ORDINAL RANKINGS?	0	-2	0	-5	-5	+5	+4	+3	0	+3
4. DID THE CARDINAL UTILITY VALUES COMMUNICATE USEFUL INFORMATION REGARDING YOUR PREFERENCES <u>BEYOND</u> WHAT WAS CONTAINED IN THE ORDINAL RANKINGS?	+2	-4	+2	-5	-5	+4	+3	+4	0	+3
5. WAS THE ASSIGNMENT OF p_ϕ^i USING THE "NO-DATA" TRAJECTORY PAIR A USEFUL EXERCISE?	-4	0	-4	-5	-5	+5	-4	-5	-2	-5
6. WERE YOUR CARDINAL UTILITY VALUES AN ACCURATE MEASURE OF THE SCIENCE VALUE OF YOUR INVESTIGATION AS FLOWN ON EACH TRAJECTORY PAIR?	+2	+5	+2	-5	-5	+5	-1	+2	-3	+3
7. WAS THE SELECTED TRAJECTORY PAIR GOOD OR BAD FOR YOUR TEAM?	+3	+3	+3	-2	+3	+4	+3	+5	+2	+5
8. WERE THE COLLECTIVE CHOICE RULES A USEFUL WAY TO EXPRESS GROUP PREFERENCES?	-1	0	+3	-5	-3	+4	-1	+4	-2	-4
9. WERE THESE COLLECTIVE CHOICE RULES AN ACCURATE MEASURE OF THE SCIENCE VALUE OF THE MISSION AS FLOWN ON EACH TRAJECTORY PAIR?	-2	-5	+2	-5	-5	+4	-2	+4	-2	+3
10. WAS THE SELECTED TRAJECTORY PAIR A GOOD OR BAD DECISION IN TERMS OF THE SCIENCE VALUE OF THE MISSION?	+3	+4	+3	-2	+3	+4	+3	+4	0	+5
11. WAS "GAMING" ATTEMPTED BY MEMBERS OF THE SSG?	+2	-	0	-5	+3	+2	+2	+3	+5	0
12. DID "GAMING" AFFECT THE SELECTION OF THE TRAJECTORY PAIR?	0	0	-1	-5	+5	0	-2	-2	+5	0
13. DID THE COALITIONS HAVE A BENEFICIAL OR UNDESIRABLE EFFECT ON THE TRAJECTORY PAIR SELECTION?	+2	+3	-2	0	-3	+2	+3	+4	+2	+5
14. WAS THE TRAJECTORY PAIR SELECTION PROCESS FAIR?	+4	+4	+2	0	+5	+4	+3	+4	0	+5
15. WOULD THE SAME TRAJECTORY PAIR HAVE BEEN SELECTED WITHOUT THE DEVELOPMENT OF THE ORDINAL RANKINGS AND THE CARDINAL UTILITY VALUES?	+2	+2	+5	+5	-2	-3	+3	-2	+2	+5
16. DID THE USEFULNESS OF THE ORDINAL RANKINGS AND THE CARDINAL UTILITY VALUES JUSTIFY THE EFFORT REQUIRED TO GENERATE THEM?	+2* 0**	0	+2	-5	+5* -5**	+5	+2	+3	0	-2
17. WOULD YOU LIKE A SIMILAR ANALYSIS TO BE PERFORMED FOR CRITICAL MISSION EVENTS SUCH AS TITAN ENCOUNTERS?	-2	0	-2	-5	-5	+5	+1	+3	-2	-3
18. WOULD YOU LIKE TO REPEAT THE ANALYSIS IN 1977 TO SELECT THE TRAJECTORY PAIR TO BE LAUNCHED?	0	0	+1	-5	-5	+5	0	+3	-5	-3

* ORDINAL RANKINGS   ** CARDINAL UTILITY VALUES

The first two questions concerned the process of the ordinal ranking of the trajectory pairs by the science teams. There was almost unanimous agreement that the ordinal ranking process had increased the science teams' understanding of the relationship between their science objectives and the characteristics of the trajectory pairs. In addition, they tended to agree that the ordinal rankings were a useful way to communicate their preferences to the other science teams. Although there was not much agreement, the responses to the two questions regarding the assignment of cardinal utility function values to the trajectory pairs indicated that for some science teams additional understanding of the trajectory pairs resulted, and additional information was communicated.

The assignment of a utility function value to the least-preferred trajectory pair based on a lottery between the most-preferred trajectory pair and the "no-data" trajectory pair was not considered to be a useful exercise. Nevertheless, five of the science teams indicated that the utility function values did provide an accurate measure of the "science value" of their investigation. All of the science teams except Science Team 3 believed that the selected trajectory pair was a good one for their own team.

The next two questions explored the usefulness of the collective choice rules. The science teams were not in agreement about whether these rules appropriately expressed group preferences, or about whether these rules provided an accurate measure of the science value of the mission as flown on each trajectory pair. They did generally agree that Trajectory Pair 26 was a good decision by the SSG in terms of the science value of the mission.

Although over half of the science teams believed that "gaming" had occurred, in the sense of biasing stated preferences in order to influence the trajectory pair selection, there was no agreement as to its effects. The science teams generally believed that the coalitions which were formed actually had a beneficial effect on the trajectory pair selection. None of the science teams believed that the trajectory pair selection process was unfair.

The science teams generally believed that the same trajectory pair would have been selected without the development of the ordinal rankings and the utility function values. Nevertheless, five of the science teams believed that the usefulness of the ordinal rankings justified the effort required to generate them.

Finally, the science teams were asked if they would like to see a similar analysis performed for critical mission events such as Titan encounters, and if they would like to see the analysis repeated in 1977 to select the actual trajectory pair to be launched. For both questions there was no agreement among the science teams, with the responses ranging from +5 to -5.

Spearman's rank correlation coefficient (Ref. 22) was used to test for correlation between Question 7: "Was the selected trajectory pair good or bad for your science team?" and other responses of the science teams, as shown in Table VIII. The responses to Question 7 are not correlated at the 0.05 level of significance with the ordinal rankings or the utility function values of the selected trajectory pair by the nine science teams. Even when the responses of the Radio Science Team and Science Team 3 are deleted from the data, the correlation is still not significant. It must be concluded that several of the science teams perceived the selected trajectory pair to be good or bad for their science investigations on the basis of criteria other than the ordinal rankings or utility function values.

The responses to Question 7 were correlated at the 0.05 level of significance with Questions 10, 14, and 18. Question 10 asked if the selected trajectory pair was a good or bad decision in terms of the "science value" of the mission. Question 14 asked if the trajectory pair selection process was fair. Question 18 asked if the science teams would like to repeat the analysis in 1977 to select the trajectory pair to be launched. Thus the opinions of the science teams concerning the selection process were correlated with whether they perceived the selected trajectory pair to be good or bad for their science investigations.

X. CONCLUSIONS

The trajectory selection process was successful because of a number of factors. By means of the mission constraints levied on the trajectory design, it was possible to separate the programmatic issues from the science issues. Thus the science teams could be asked to evaluate the trajectory pairs solely on the basis of their science preferences. Another important factor was that compatible alternatives actually existed -- this is partially fortuitous, but more strongly a result of the detailed project planning and coordinated science investigation selection process. The collective choice rules were in general agreement, reflecting this compatibility.

Table VIII

A Statistical Test for Correlation with Question No. 7

QUESTION No. 7: WAS THE SELECTED TRAJECTORY PAIR GOOD OR BAD FOR YOUR SCIENCE TEAM?

r_s = SPEARMAN RANK CORRELATION COEFFICIENT

CORRELATION WITH QUESTION No. 7	r_s	LEVEL OF SIGNIFICANCE
ORDINAL RANKINGS OF SELECTED TRAJECTORY PAIR BY 9 SCIENCE TEAMS	0.35	NOT SIGNIFICANT AT 0.05 LEVEL
ORDINAL RANKINGS OF SELECTED TRAJECTORY PAIR BY 7 SCIENCE TEAMS (RSS AND SCIENCE TEAM 3 DELETED)	0.40	NOT SIGNIFICANT AT 0.05 LEVEL
UTILITY FUNCTION VALUES OF SELECTED TRAJECTORY PAIR BY 9 SCIENCE TEAMS	0.52	NOT SIGNIFICANT AT 0.05 LEVEL
UTILITY FUNCTION VALUES OF SELECTED TRAJECTORY PAIR BY 7 SCIENCE TEAMS (RSS AND SCIENCE TEAM 3 DELETED)	0.47	NOT SIGNIFICANT AT 0.05 LEVEL
QUESTION No. 10: WAS THE SELECTED TRAJECTORY PAIR A GOOD OR BAD DECISION IN TERMS OF THE SCIENCE VALUE OF THE MISSION?	0.91	< 0.01
QUESTION No. 14: WAS THE TRAJECTORY PAIR SELECTION PROCESS FAIR?	0.74	< 0.05
QUESTION No. 18: WOULD YOU LIKE TO REPEAT THE ANALYSIS IN 1977 TO SELECT THE TRAJECTORY PAIR TO BE LAUNCHED?	0.64	< 0.05

The generation of the candidate trajectory pairs was an essential part of the trajectory pair selection process, even though it lies outside most of the formalism presented in this article. The generation of the trajectory pairs was an iterative process, requiring the science teams to identify those general characteristics of the trajectories which were required by their science investigations and requiring the JPL trajectory analysts to construct trajectory pairs containing these characteristics. As the process proceeded, better trajectory pairs were constructed. Of the original list of 24 trajectory pairs which were documented and distributed to the science teams for consideration, four were dropped, and only four were subsequently ranked in the top 10 by the rank sum collective choice rule. None were among the last three in contention. Finally, as a result of the information exchange between the science teams and the JPL trajectory analysts, it was possible to further improve the trajectory pair selected from the candidate list.

With the information generated in the trajectory selection process, an improved set of candidate trajectory pairs could now be generated. Certainly more trajectory pairs with improved ring occultation characteristics would be included, and possibly trajectory pairs could be constructed with high rankings by all the science teams. Some trajectory pairs from this set could in principle be preferred to the selected trajectory pair.

The science teams willingly participated in the trajectory selection process because they recognized the necessity for them to understand the trajectory alternatives and to develop their science investigation requirements, and they recognized that if a consensus could be reached among the science teams, the Project Manager would accept the science recommendation as the Project standard trajectory pair. Also, the science teams had participated in the generation of the trajectory pairs, and the set of candidate trajectory pairs contained at least one trajectory pair which was considered as very good by each science team.

The science teams were able to adequately express their preferences for the candidate trajectory pairs. The ordinal rankings by the science teams were essential to this process, and only minor problems were encountered in eliciting this information. The cardinalization lotteries and the reasons for their use were not endorsed by all the science teams. Nevertheless, all of them did submit cardinal values, based either on the cardinalization lotteries or on a formula weighted and evaluated for each trajectory characteristic.

Since the normalization lotteries did not appear to properly encode the preferences of the science teams for their least-preferred trajectories, it was necessary to test the sensitivity of the collective choice results to the normalization assumptions through the use of two other normalization procedures. As was shown in Table IV, whether the utility function values were scaled upward from 0.0, p^i_ϕ, or 0.6/0.8 made only minor differences in the rankings of the trajectory pairs by the collective choice rules.

While gaming and coalition-formation did occur, there is no evidence that it influenced the trajectory pair selection. Some science teams may have assigned low utility function values to a large number of trajectory pairs in an attempt to bias the selection process toward a few trajectory pairs with specific characteristics. The Radio Science Team (RSS) unfortunately biased themselves out of the analysis by assigning to a large number of trajectory pairs the minimum value that could be negotiated with the Project. As a result, the Radio Science Team had no differential effect on the collective choice values of the nine trajectory pairs ranked highest by the rank sum collective choice rule.

One other problem with respect to the science team evaluation of the trajectory pairs should be mentioned. Agreement was never achieved on the precise criteria to be applied to the evaluation. Three issues never completely resolved were: (1) whether the two trajectories of each pair should be considered as providing complementary or redundant science, (2) whether the total mission or only the encounter aspects of the trajectory pairs should be considered, and (3) whether each team should consider the trajectory pairs in the narrowest context as satisfying the requirements of their science team, or in a broader context of also satisfying the requirements of other science teams with complementary objectives.

Could the selected trajectory pair have been identified without the decision analysis formalism? While there is no definitive answer to this question, there are two indications that it could not have been. First, the SSG was given several opportunities to state a science-preferred trajectory pair, and none was forthcoming. Second, the Project and the science teams earlier had been working with a trajectory pair developed during the preceding year. It had been assumed that this earlier trajectory pair was quite satisfactory, and it could have been expected to rank high among the other alternatives. This earlier trajectory pair was included on the candidate list as Trajectory Pair 20. It was most surprising to find that Trajectory Pair 20 was ranked 28 by the rank sum collective choice rule!

Clearly the ordinal rankings of the science teams were essential to the selection process. These ordinal rankings and the rank sum collective choice rule probably would have been sufficient to ultimately identify either Trajectory Pair 26 or 31 as the science-preferred trajectory pair. Nevertheless, the authors conclude that the cardinal utility evaluation by the science teams was an important part of the selection process. The cardinal utility evaluation aided the selection between Trajectory Pairs 26, 29, and 31, it tested the collective choice analysis for sensitivity to strength of preference not revealed by the ordinal rankings, and it permitted a wider range of collective choice rules to be used in the analysis.

In summary, the methodology presented in this article did provide a suitable framework for each science team to assess its preferences, and to communicate these preferences to the other science teams. The science teams were then able to arrive at a consensus in an effective manner and to recommend to the Project a science-preferred trajectory pair which was subsequently implemented as the Project standard trajectory pair.

REFERENCES

1. "Mariner Jupiter/Saturn 1977 Project Plan," Project Document 618-5, Jet Propulsion Laboratory, Pasadena, California, December 8, 1972 (an internal document).

2. Schurmeier, H. M., "The Mariner Jupiter/Saturn 1977 Mission," to be published.

3. Borras, J. A., "Science Experiment Value Functions for Mariner Venus 1967, IOM 312.4-581, Jet Propulsion Laboratory, Pasadena, California, November 17, 1966 (an internal document).

4. Borras, J. A., "Science Value Functions and Aiming Point Constraints — Mariner Mars 1969," Project Document 605-148, Jet Propulsion Laboratory, Pasadena, California, December 1968 (an internal document).

5. Haynes, N. R., Bollman, W. E., Neilson, R. A., Nock, K. T., and Travers, E. S., "Mariner Mars 1971 Adaptive Mission Planning," AIAA Paper No. 72-944, presented at the AIAA/AAS Astrodynamics Conference, Palo Alto, California, September 11-12, 1972.

6. Shirley, D. L., "MVM'73 Mission Analysis: Application of a Black Art," Jet Propulsion Laboratory, Pasadena, California (to be published).

7. Bourke, R. D., Miles, R. F., Jr., Penzo, P. A., Van Dillen, S. L., and Wallace, R. A., "Mariner Jupiter/Saturn 1977 – The Mission Frame," Astronautics and Aeronautics, Vol. 10, No. 11, 42-49 (November 1972).

8. Keeney, R. L., "Multiplicative Utility Functions," Operations Research, Vol. 22, No. 1, 22-34, 1974.

9. Fishburn, P. C., Utility Theory for Decision Making, Wiley, New York, New York, 1970.

10. Raiffa, H., "Preferences for Multiattributed Alternatives," RM-5863-DOT/RC, The Rand Corporation, Santa Monica, California, April 1969.

11. v. Winterfeldt, D., and Fischer, G. W., "Multi-Attribute Utility Theory: Models and Assessment Procedures," Technical Report 011313-7-T, Engineering Psychology Laboratory, The University of Michigan, Ann Arbor, Michigan, November 1973.

12. Beerer, J. G., Penzo, P.A., and Wallace, R. A., "Mariner Jupiter/Saturn 1977 Preliminary Trajectory Characteristics," Project Document 618-16, Jet Propulsion Laboratory, Pasadena, California, May 1, 1973 (an internal document).

13. "Mission and Science Requirements," Vol. 1: "Mission Requirements," Project Document 618-51, Jet Propulsion Laboratory, Pasadena, California, September 24, 1973 (an internal document).

14. "Mission and Science Requirements," Vol. 2: "Science/Mission Interface," Project Document 618-51, Jet Propulsion Laboratory, Pasadena, California, July 9, 1973 (an internal document).

15. "Investigation Descriptions for the Mariner Jupiter/Saturn 1977 Mission," Project Document, Jet Propulsion Laboratory, Pasadena, California, April 5, 1973 (unpublished internal document).

16. Penzo, P. A., "Science Objectives and the Mariner Jupiter/Saturn 1977 Mission Design," AIAA Paper No. 74-780, AIAA Mechanics and Control of Flight Conference, Anaheim, California, August 5-9, 1974.

17. Wallace, R. A., "Trajectory Design Candidates for MJS77," EM 392-154, Jet Propulsion Laboratory, Pasadena, California, August 22, 1973 (an internal document).

18. Miles, R. F., Jr. and McLaughlin, W. I., "Evaluation of MJS77 Trajectory Pairs," EM 392-152, Jet Propulsion Laboratory, Pasadena, California, August 20, 1973 (an internal document).

19. Long, J. E., "Evaluation of Candidate Trajectory Pairs," Letter to SSG Members, Jet Propulsion Laboratory, Pasadena, California, September 20, 1973 (an internal document).

20. von Neumann, J., and Morgenstern, O., Theory of Games and Economic Behavior, Princeton University Press, Princeton, New Jersey, 1947.

21. Sen, A. K., Collective Choice and Social Welfare, Holden-Day, San Francisco, California, 1970.

22. Siegel, S., Nonparametric Statistics, McGraw-Hill, New York, New York, 1956.

23. Fishburn, P. C., "A Comparative Analysis of Group Decision Methods," Behavioral Science, Vol. 16, 538-544, 1971.

24. Harsanyi, J. C., "Cardinal Welfare, Individualistic Ethics, and Interpersonal Comparisons of Utility," J. Political Economy, Vol. 63, 309-321, 1955.

25. Marschak, J., "Rational Behavior, Uncertain Prospects, and Measurable Utility," Econometrica, Vol. 18, 111-141, 1950.

26. Luce, R. D., and Raiffa, H., Games and Decisions, Wiley, New York, New York, 1958.

27. Nash, J. F., Jr., "The Bargaining Problem," Econometrica, Vol. 18, 155-162, April 1950.

28. Bonnardeaux, J. A., Dolait, J. P., and Dyer, J. S., "The Use of the Nash Bargaining Model in Trajectory Selection," Working Paper No. 214, Western Management Science Institute, Los Angeles, California, May 1974.

29. Rawls, J., A Theory of Justice, The Belknap Press of Harvard University Press, Cambridge, Massachusetts, 1971.

30. Riker, W., "Voting and the Summation of Preferences: An Interpretive Bibliographical Review of Selected Developments during the Last Decade," American Political Science Review, Vol 55, 900-911, 1961.

31. Pickering, W. H., "The Grand Tour," American Scientist, Vol. 58, No. 2, 148-155, March-April 1970.

32. "Outer Planets Grand Tours Mission Requirements," Project Document, Jet Propulsion Laboratory, Pasadena, California, January 21, 1972 (an internal document).

33. "Outer Planets Science Steering Group. Mission Definition Phase. Grand Tour," Project Document 618-7, Jet Propulsion Laboratory, Pasadena, California, May 15, 1972 (an internal document).

34. "Outer Planets Science Steering Group. Mission Definition Phase. Mariner Jupiter/Saturn 1977," Project Document 618-8, Jet Propulsion Laboratory, Pasadena, California, May 15, 1972 (an internal document).

35. "Announcement of Flight Opportunity for Mariner Jupiter/Saturn 1977 Mission," Proposal Package, National Aeronautics and Space Administration, Washington, D. C., May 1972.

36. "Opportunities for Participation in Space Flight Investigations. Mariner Jupiter/Saturn 1977 Mission," Memo Change 45, NHB 8030.1A, National Aeronautics and Space Administration, Washington, D. C., April 14, 1972.

37. Long J. E., and Vrebalovich, T., "MJS77 SSG Meeting on 22/23 October 1973," Jet Propulsion Laboratory, Pasadena, California, December 6, 1973 (an internal document).

38. Penzo, P. A., Wallace, R. A., Beerer, J. G., and Smith, D. B., "SSG Trajectory Data Package for Selected Trajectory Pairs," IOM 392.1-20-PAP, Jet Propulsion Laboratory, Pasadena, California, October 19, 1973 (an internal document).

39. Beerer, J. G., Penzo, P. A., and Wallace, R. A., "Mariner Jupiter/Saturn 1977 Standard Trajectories," Project Document 618-113, Jet Propulsion Laboratory, Pasadena, California, February 8, 1974 (an internal document).

NASA — JPL — Coml, L.A., Calif.